**2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM**
**POWER AND ENERGY MINI-SYMPOSIUM**
**AUGUST 17-19 DEARBORN, MICHIGAN**

# A Modern Diesel Engine Concept for Military Application

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**ABSTRACT**

*When seeking a diesel engine to power their advanced military prototypes, military vehicle developers have a mostly unsuitable list of options. Typically, the decision comes down to a compromise of undesirable components and outdated technology. A military supplier will likely face an option between an advanced diesel engine specifically developed to achieve modern emission requirements or an archaic powerplant that has decades old specific power level. These engines were not developed for the unique requirements of a military application. A diesel engine developed specifically for the military could take advantage of opportunities associated with the application and produce a lighter, more powerful and more capable vehicle.*

## INTRODUCTION

With a reduced emphasis on emission levels a modern combustion system can be applied that is not forced to make compromises for an application of EGR or aftertreatment systems. Instead the combustion system would focus on power, efficiency, reduction of noise and low soot emissions. As a part of the advanced combustion system, a multi-fuel capable fuel injection system would eliminate issues with operation on military fuels and be ready for a military adoption of renewable biofuels and fuel blends.

The excessive weight inherent in older engine designs can be avoided through a use of modern materials and a design approach targeting the requirements of the application. Reduced weight and increased specific power has a direct impact on the desire for increased acceleration, agility and fuel efficiency.

Significant research activity has been applied to an additional combustion system to be placed on board as an APU for low speeds and idling conditions. Such operating conditions are a large portion of the operation of most military vehicles and thus have a significant impact on the fuel consumption as well as the heat and noise signature. Converting the main engine to a smaller displacement is a more elegant, durable and cost effective solution than adding additional hardware. With a clean sheet design a displacement on demand can be incorporated to provide an improved fuel economy with a minimal increase in hardware and complexity, including reduced space claim and maintenance costs.

Currently, a modern engine concept uniquely suited to take advantage of these specific boundary conditions does not exist and a carry over application only comes with disadvantages and compromises. A military specific engine development would not only allow a choice for a vehicle developer but would provide an opportunity to achieve all the desired and advantageous characteristics within their specific packaging requirements. With modern development tools and the right expertise and experience such a development program could be cost effectively completed over an aggressive time schedule.

## LACK OF MILITARY OPTIONS

Today’s production engine market does not provide the military minded vehicle manufacturer with desirable options. Engines developed for the passenger car and heavy-duty vehicle markets are highly focused on emission control to meet applicable emission standards. These engines incorporate complex exhaust gas recirculation and aftertreatment systems that are fully integrated into the engine control and operation. Specifically, these emission control systems are implemented and calibrated to function efficiently with the supporting hardware. A simple desire to remove an emission control device, such as EGR, will result in a severely compromised operation, which will at the very least have significantly reduced performance. This is despite a significant effort to remove its control from both the hardware and software system. In a previous publication [1], FEV outlined these challenges and the implications of adopting an emission-ized engine concept for a military application that is not bound by strict emission standards.

Beyond the concern for emission control systems, diesel engines currently available in the market do not reach the desired power to weight targets sought by a modern military vehicle developer. Often compromises must be accepted in weight or power level, resulting in a vehicle that is unable to reach the performance and mobility targets set by the manufacturer and needed by its customers.

The diesel engine market place, both foreign and domestic, offers either a heavy-duty engine that meets the power levels but weighs too much or a light-duty engine that meets weight requirements but is short on power output. Taking an example from current production, a heavy-duty diesel engine capable of 260 kW weighs in at over 530 kg. This significant weight is a result of a reliance on old technology materials, such as cast iron for the engine block and cylinder head, which when combined account for nearly 50 % of the total engine weight.

Military vehicle manufacturers could offer a much superior and more capable product if a diesel engine with significantly better specific power existed. As a general target, the engine weight should be reduced significantly and approach 230 kg. A power output greater than 250 kW is desired for this application, pushing the limits of what is currently available at this weight class.

## DESIRABLE ATTRIBUTES/FUNTIONALITY

Due to their unique application, diesel engines developed for military use can take advantage of a reduced emphasis on emission control and focus on power output and fuel efficiency. In addition, with a clean sheet military focused design, the engine can provide capability not currently available in the commercial market.

### *Capability*

Capability is of prime importance to a military vehicle. In addition to payload, acceleration and maneuverability are critical attributes that must be maximized. To allow the vehicle to exhibit these characteristics it must be equipped with a powerful and lightweight powertrain. At the heart of this powertrain, a combustion engine that is capable of delivering a class-leading specific power is desired.

### *Efficiency*

Without the need for EGR systems or aftertreatment, the engines hardware and calibration can be optimized for efficiency. The application of an EGR system results in a compromised air handling system and typically a throttling of the intake. Exhaust gas aftertreatment systems at the very least contribute significant backpressure to the engine, and often require special events to keep them functioning. Fuel injection is typically retarded from the best efficiency point to reduce the production of NOx emissions. Each of these emission control approaches results in a loss of efficiency and thus a higher fuel consumption. With high fuel costs and difficult logistics in the battlefield that directly impact the speed of a military operation, improved engine efficiency is highly desirable for a military engine concept.

### *Operating Signature*

Although emission compliance is not currently a requirement for military applications, the operating signature of military vehicles must be addressed to reduce detection in the battlefield. Visible smoke from the tailpipe of the vehicle must be minimized to maintain a low visual signature. This is true for idle conditions, full load and transient operation where the operator is aggressively accelerating the vehicle.

In addition to the visual signature, the noise signature of the engine must also be addressed. The common diesel engine noise, if not mitigated, can lead to early detection in the battlefield and endanger the vehicles occupants and the supporting force. Stealth operation can likely not be reached however reduced visual and noise signature can help to protect military troops and allow a moderate level of non-detection.

### *Auxiliary Power*

To further address the desire for fuel efficiency in the battlefield, many military vehicle manufacturers have investigated the application of auxiliary power units (APU) to provide the vehicle with the needed electrical power during times of stationary operation. As apposed to idling a large displacement main combustion engine, a small displacement APU can supply just the required electrical power for on-board electronics while keeping fuel consumption to a minimum. Such electronics could include navigation, communication and combat specific hardware. In addition, the cabin temperature could be maintained through the operation of this APU for the comfort and thus optimum function of the occupants.

The operation of an APU in place of a large displacement main engine can also add to the desire for a minimized operating signature. Due to its smaller displacement and lower required output during stationary operation, the APU’s noise, heat and smoke signature can be better mitigated.

Depending on the configuration and the sizing of this auxiliary power unit, the option to utilize it for low vehicle speed operation can also benefit both fuel consumption and the vehicle’s detectability.

### *Fuel Compatibility*

First and foremost a military specific engine must be capable of operating on diesel fuel as well as various military jet fuels. The capability for limited operation on gasoline is also an advantage for emergency situations.

Beyond these typical fuels, the military has recently been investigating the adoption of alternative fuels to power its fleets and reduce the reliance on foreign oil supplies. Such alternative fuels would move away from conventional crude oil based fuel production and investigate Fischer Tropsch produced fuels and fuel produced from domestic renewable sources.

Specifically the US Air Force is conducting test flights with a jet fuel produced synthetically through the Fisher Tropsch (FT) process. These flights have been successful and they remain on target to certify their entire fleet on FT fuel by 2011. Both the US Air Force and the US Navy has more recently begun to investigate hydrotreated biofuels derived from renewable sources. Domestic plant sources are being explored for their superior quality as a fuel producers and the fact that they do not compete with food crops. Both the military and the US Energy Department are putting forth significant effort to confirm safe and reliable operation with such

Providing a fuel system and a combustion system that is capable of operating on most any fuel source could be a huge advantage in the battlefield. This is especially true when considering the possibility of utilizing fuel supplies that are captured during battle operations.

A fuel system that is capable of operating properly and exhibiting the required durability on most any fuel type is a significant advantage and most likely a requirement for future applications.

### *Durability and Maintenance*

Engine durability, longevity and reliability must be of prime importance when developing an engine specifically for military application. Although reliability and durability are strongly considered in the development of commercial heavy-duty engines, an application for military vehicle is of extreme importance, where the safety of its occupants directly depends on its proper operation. Durable operation, including reliable starts and acceleration, under both conventional and extreme environments is a must.

Maintenance of military vehicles must often be conducted in the field of battle. The troops operating these vehicles in this demanding environment would benefit significantly from a configuration that allows minimal scheduled maintenance. When maintenance is required it should be simple and able to be conducted with little to no tooling. In addition the various operating environments must be considered to address the use interval for replaceable items such as air filters.

## A MODERN DIESEL ENGINE CONCEPT

The intention of the following section is to build a concept diesel engine specifically targeted for military application. Each of the desired attributes discussed above will be addressed along with a currently available technical solution. Unique features will be presented that when combined will result in a combustion engine that would provide a military vehicle with superior power output and efficiency while eliminating the compromises that are typically associated with the conversion of a commercially available engine.

### *Advanced Combustion System*

Although the application of advanced diesel combustion concepts are well know, they have to date been applied in an environment of emission control. Thus the full benefit of an advanced combustion system for fuel efficiency and power has been filtered by the need to apply EGR and limit emission production. With a reduced demand on emission reduction, advanced combustion approaches can be exploited for their full potential for performance improvement.

By easing the constraint of emission control, the ability to reach high power density is governed by the peak piston speed, the peak cylinder pressure and the heat rejection level. Engine designers seeking to maximize a concepts power density must be carefully consider each of these limiting factors. In Figure 1 these factors are quantified and some possible alternative approaches are suggested.

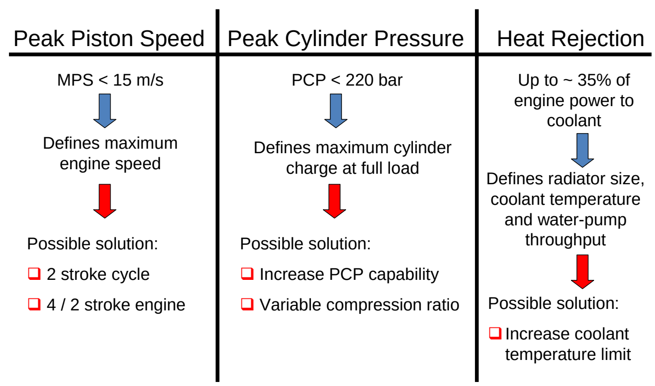


Figure 1: Possible High Power Density Solutions

As the desire to increase power output pushes to increase engine speed, the peak piston speed must not be breeched. This limit can be addressed through alternative concepts such as the 4/2 stroke engine. This solution has the potential to maintain superior fuel economy under part load conditions but provide superior power levels at full load. [1]

A concept that has the potential to address the peak cylinder pressure limit is variable compression ratio. The advantage of being able to switch between high and low compression ratio on the fly allows increased power output levels without violating peak-cylinder pressure limitations but still retain the fuel consumption benefits and cold start ability that are inherent with high compression ratios. [1]

Finally, the limit of heat rejection capability must be observed to protect the engine against damage. An option to reduce the amount of heat rejection is to maintain more heat in the cylinder and thus increase the engine operating temperature. Any attempt at increasing the engine operating temperature must carefully consider the engine component material. Significant research has been applied to the use of ceramic insulation in the combustion chamber to reduce the heat rejection and provide more thermal efficiency. To date these programs have fallen short to provide a substantial improvement while retaining the necessary robustness to the configuration.

### *Combustion Control*

Recently durable cylinder pressure transducers have been installed in production engines and provide the ability to monitor the combustion system in real-time. These transducers are integrated into the glow plug package and do not require additional modification or space claim in the cylinder head. Specifically, the glow plug incorporates a strain gauge whose resistance changes as a function of deformation. From this deformation a compression force is calculated and this force is proportional to the cylinder pressure. In current production applications this information allows a cylinder by cylinder indexing of the center of combustion and thus maintains performance and significantly narrows the range of emission levels.

Beyond this approach, such technology can be expanded to allow safe operation of the engine on a range of fuels. **Figure 2** shows a control strategy designed to control the combustion event in real-time. Specifically this strategy utilizes the cylinder pressure information to adapt the fuel injection timing. With such fast and accurate control of the injection event the engine can immediately respond to a change in fuel type or modify the combustion for power or efficiency based on a request. As mentioned previously many US military units are currently investigating the use of various alternative fuels. With such control the specific properties of the fuel are less critical as the engine can automatically adapt to optimize combustion on the available fuel.

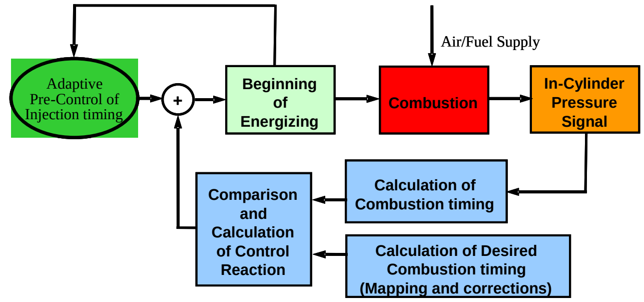


Figure 2: Cylinder Pressure Based Control Strategy

Cylinder pressure control systems are well suited for military applications due to the current multi-fuel strategies being applied, for instance to operate on both DF2 and JP-8. This approach would eliminate the need for multiple strategies and calibration effort and further expand the fuel compatibility limit. The operators can thus choose their fuel based on what is of easiest access and/or lowest cost, even make use of fuels captured from opposition armies. Finally, this approach can allow real-time and automatic optimization of the performance, emissions (smoke), fuel economy and noise for a wide selection of fuel types.

### *Fuel System*

Due to the desire to operate on multiple fuels, including those that exhibit poor lubricating properties, the injection equipment must be properly specified. With varying properties associated the injection equipment must be tolerant and build to function consistently with a range of specification. **Table 1** displays the property differences found in two conventional military fuels, Diesel and JP-8. This table begins to describe the challenge for fuel compatibility but the system will be further challenged as additional biofuels are introduced.

Table 1: Fuel Property Comparison

| Properties | Unit | US Diesel | JP 8 |
|---|---|---|---|
| Density @ 15°C | kg/l | ~840 | <800 |
| Viscosity @ 40°C | mm²/s (cSt) | 1.9 … 2.3 | 1.2 … 1.4 |
| Cetane Number | | 42 | 53 |
| Distillation | | | |
| 10% Recovery | °C | 180 max. | 190 |
| 50% Recovery | °C | 255 max. | 200 |
| 90% Recovery | °C | 315 max. | 230 |
| Heat of combustion | kJ/kg | 42600 | 43100 |
| Sulfur content | ppm | <15 ppm Ø<8 ppm | <3000 ppm Ø ~ 100 ppm |
| Cloud point | °C | -35 | -49 |
| Flash point | °C | 38 | 63 |
| Lubricity (HFRR) | µm | ~500 | >700 |

An engine designer must decide on which fuel injection equipment to apply based on the peak pressure and functionality requirements as well as the engine configuration. The common fuel injection system options available for a diesel engine concept are provided in **Figure 3**.

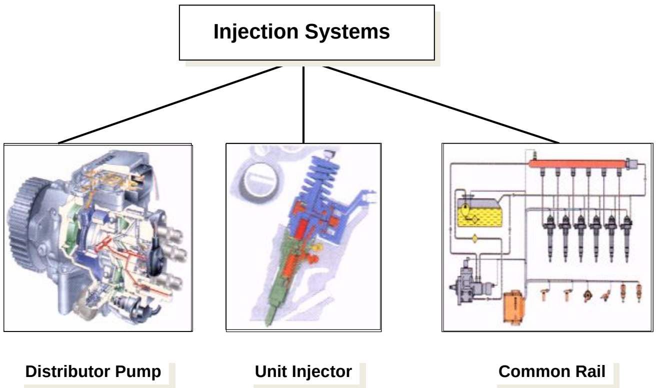


Figure 3: Fuel Injection System Options

A common rail injection system allows great flexibility for control of the combustion and thus its effect on emissions, noise and efficiency. The ability to apply multiple injection events to achieve the desired combustion behavior is a significant advantage.

For compatibility with military jet fuels, the fuel system must be prepared for functionality and durability despite significant property differences when compared to conventional diesel fuel. Density, viscosity, heating value and lubricity are major property differences found in these fuels. Common rail injection pumps in particular are designed for operation on diesel fuel and the hardened components within the pump do not consider operation on with low lubricity fuels, such as JP-8 or gasoline. [1] Therefore for a military application the hardening of the high pressure pump components is mandatory unless the pump is redesigned to utilize engine oil for lubrication.

As mentioned above, the desire to adopt domestically produced alternative fuel types is strong within the US Military. This desire is backed heavily by the heads of each military branch and programs are being conducted to verify engine operation on each fuel as it becomes available. New fuels continue to become available, with fuels produced from algae and camelina as some of the current favorites. It is important to consider the unique properties of such plant based fuels and produce injection equipment that is 100% compatible, both for functionality and durability.

In addition to compatibility with various fuel types, the injection pressure capability of the fuel injection system can provide additional advantages. Injection pressure in diesel combustion systems has continued to rise over recent years. This increase has been urged by a desire for reduced particulate matter formation as well as improved efficiency. The introduction of EGR in commercial engines has resulted in an increase in particulate matter. This increase can be partially mitigated by increasing the injection pressure and improving the in-cylinder air utilization and mixing.

Military applications can apply increased injection pressures to achieve an increase in specific power. The higher injection pressure allows the ability to achieve a greater injection quantity for the same injection opening time. The engine can then tolerate higher engine speed and thus increase the power output. These increased pressures can also allow for a reduced exhaust gas temperature that can help to protect components such as the turbocharger and aid to reduce the heat signature of the vehicle.

### *Air Handling System*

Multi-stage air handling systems, allow significant increases in specific power, allowing high horsepower availability in smaller, lighter powertrain packages. Lack of advanced emission control systems like EGR, further free up exhaust enthalpy availability providing a positive synergy with staged boosting systems. Aggressive downsizing measures demand boost levels that exceed the capability of a single turbo machine. A two-stage turbo system allows the necessary pressure ratio to be spread equally among two turbo machines, while also maintaining optimal operating efficiency across the engine speed and load range. Optimal control of exhaust admission ratios to the two units can be accomplished with the use of proportional bypass valves, and electronic controls. Another important consideration is sufficient charge cooling capacity to address the additional heat rejection associated with higher compression pressures. Multiple turbomachines can also be considered a fail-safe, whereby should a failure of one unit occur; partial engine power could still be maintained. This would require some creative layout of hot and cold side bypasses, such that failure of either the high or low pressure stage would not prevent the remaining turbo from being functional.

### *Advanced Materials*

Based on the use of conventional materials in heavy-duty engines that are typically applied to military applications, there is a strong potential for weight savings through a fresh look at base materials. By taking an example of a V8 heavy-duty engine in the 6-7 liter class, the total engine weight is over 500 kg. Nearly 140 kg of this weight is represented by the engine block, which is constructed of case iron. The substitution of compressed graphite iron (CGI) could allow approximately 20 % reduction in weight. Aluminum can also be considered for the cylinder block if peak cylinder pressures are maintained below 180 bar. Aluminum could provide approximately 35 % reduction in weight.

With aluminum substituted for the cast iron cylinder head an additional 50 % savings in weight can be realized. Based on its significant contribution to the overall weight, changing the cylinder head material to aluminum could provide a significant benefit.

An often overlooked yet significant contributor to the total engine weight is the exhaust manifold and turbocharger assembly. The exhaust manifold or manifolds are often of cast iron construction as well. By applying a fabricated concept for the manifold and turbocharger assembly the estimate for weight savings approaches 35 %.

Through careful application of these material changes as well as a through approach to minimizing the weight of other engine components, the final engine configuration can provide a significant weight reduction and thus a reduced vehicle weight and an improved vehicle performance.

### *DOD*

Recently research efforts have been applied to identify and develop an appropriate APU for use within a military vehicle. The concept is to provide a more efficient operation for times when the full capability of the main engine is not required, for instance when on-board systems are functioning but the vehicle is stationary. The issue with such an approach is the necessity for a completely separate combustion engine. Not only will this additional engine demand significant space on board the vehicle, it will also require duplicate systems such as those needed for cooling and air and fuel supply. The APU will also need to be maintained along with the main engine adding to the efforts required of the operators.

With a combustion engine already on-board for vehicle propulsion, a more efficient and elegant solution would be to utilize this existing main engine hardware in a reduced capacity. Rather then duplicate systems and add a second combustion engine, the main engine can be operated on fewer cylinders. Displacement on Demand systems have already reached the passenger car market and are applied to provide fuel savings at times of reduced power requirement. By applying this approach more aggressively for a military engine, the main engine hardware can be used to power the necessary electronics during idle conditions. This approach would provide obvious fuel savings by only operating a few cylinders of the multi-cylinder engine but it would also eliminate the need to add an on-board APU.

An important consideration for successful execution of an on-demand displacement powertrain is detailed calibration. Key aspects to be considered include hysteresis levels between full and reduced cylinder operation, speed thresholds below which reduced cylinder operation may not be feasible from a drivability and handling standpoint, as well as the requirement to switch back and forth quickly and seamlessly.

## HYBRIDIZATION

Despite its associated increase in complexity and weight, the concept of hybridization can offer many advantageous characteristics for a military vehicle. In particular, an electric hybrid can allow a significant reduction in noise and heat signature for portions of its operation when the electric motors are able propel the vehicle and run support electronics in place of the combustion engine. The allowable time for this operation is of course dependent on the type and quantity of batteries carried on-board.

In combination with the DOD concept outlined above, the hybrid configuration can allow the engine to operate in an efficient ‘sweet spot’ at a reduced capacity and charge the battery pack. Again this would be particularly useful for idle operation and when the vehicle is stationary but in need of operating electrical loads. The benefit in fuel savings would be significant when compared to continuously idling the main combustion engine at its full capacity for these types of operating scenarios.

During standard drive operation a hybrid configuration can make use of regenerative braking to increase the efficiency of the vehicle and reduce the demand for support from fuel tankers. Also the presence of electric motors can allow the application of a launch assist. Possible due to the stored energy in the batteries, this ‘boost’ in acceleration can be applied when needed by the vehicle operator, a capability that would prove useful in tactical situations.

As mentioned above, the desire to apply a hybrid concept must be met with consideration for the additional space and weight claim as well as the significant increase in hardware and control system complexity.

## FINAL CONFIGURATION

The final engine configuration will be a reflection of the ability to apply the presented technologies to improve fuel efficiency and increase power density. Of course any desire to apply these technologies will be met with a cost consideration. Many technologies have been suggested that can provide advantages for a military specific engine application. Achieving the goal of developing a superior military engine configuration will require a fresh approach to the design from the start and redirects focus from emission compliance to engine performance and efficiency. This clean sheet approach avoids the well know difficulty in adapting a current production engine by stripping it of much of its emission control equipment. As mentioned this approach would only result in a compromised solution that does not exhibit any of the potential military attributes suggested herein.

As a general target the military application shall exhibit power output of greater than 250 kW. This will likely be provided in a V6, V8 or I6 configuration and account for a total weight that approaches 230 kg. The engine manufacture, in close cooperation with the vehicle manufacturer, must identify which unique technologies are incorporated to reach these targets as well as provide the military user with a superior war-fighting machine.

## CONCLUSIONS

The goal of this paper was to compile all the specific requirements of a combustion engine for a military application along with the many advantageous features and provide a state-of-the-art solution that will result in a superior military vehicle. The need for this approach was a result of a complete lack of engine options available to the military vehicle manufacturer. As mentioned the combustion engines currently available in the market are developed with emission compliance as a major consideration and this results in a severely compromised performance and efficiency.

By beginning with a clean sheet engine development that weighs military attributes heavily and reduces the focus on emission levels, an engine can be produced that directly suited to a military vehicle. Such a product does not currently exist in the market place and an attempt to convert existing emission compliant production engines would prove to be expensive, time consuming and ultimately compromised. In addition this approach would not be able to incorporate all the military specific features outlined in this text. A modern diesel engine specifically designed and developed for military application would provide superior performance, unique features and improved efficiency, and thus allow a combat force a significant advantage in the battlefield.

## REFERENCES

[1] Tatur et al.: Challenges in Adapting State-of-the-Art On-Highway Diesel Engine Technologies to Meet Military Specifications; GVSETS, Dearborn 2009